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RESEARCH ARTICLE

Sensitivity and Robustness Issues of Operating Envelopes in Unbalanced Distribution Networks

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ABSTRACT The fast-growing uptake of distributed energy resources (DER), such as home photovoltaic (PV) and battery systems and electric vehicles, has introduced new challenges in the operation of low-voltage distribution networks (LVDNs). High levels of DER can produce large swings in power flow from the day (low-demand, high PV exports) to the night (high-demand) that can push the LVDN network to its operational limits. Network operating envelopes aim to maximise network capacity utilisation through the implementation of dynamic customer capacity limits, where DER exports or imports are constrained at times of network congestion and otherwise relaxed to potentially higher levels than those realisable through traditional static customer capacity limits. A common assumption underlying the implementation of operating envelopes is that operational constraint violations will be avoided if the realised demands of customers under dynamic connections all fall within their capacity envelopes. However, this assumption needs more careful consideration in the light of strong unbalance and mutual phase couplings common in LVDNs. This paper analyses phase voltage level sensitivities to customer demand levels and demonstrates that voltage violations can still occur when all customers are within their limits. These results, illustrated by experimental studies based on a two-bus example and a real representative Australian LVDN, underline the importance of incorporating uncertainty in the calculation of operating envelopes.

INDEX TERMS DER architecture, distribution network, hosting capacity, operating envelopes, unbalanced three-phase power flow, voltage violations.

I. INTRODUCTION

Due to encouraging policies and incentives from government policies, Australia is experiencing a remarkable renewable energy development in recent years, taking the top spot worldwide in the penetration level of distributed PV systems installation by residential customers [1].

Distributed PV panels, which are usually connected to the LVDN in Australia, benefit residential customers by reducing their electricity bills. However, they can also cause operational problems, e.g., voltage unbalances that can lead to deteriorated power supply quality, increasing power loss and accelerated ageing of three-phase equipment, over-loading in the distribution transformer and, most commonly, the

over-voltage issues [2], [3]. All these issues could undermine the network's capability to host more PVs in the future. Correspondingly, there is a compelling need for distribution network service providers (DNSPs) to improve network hosting capacity estimation and utilisation in order to integrate more distributed energy resources (DERs).

Hosting capacity is usually defined as the maximum level of DER that a particular network can withstand without violating any operational limits. Such limits could be on voltage magnitude (VM) level, power flows in both distribution transformer and distribution lines, voltage unbalance and power quality indicators such as flicker and harmonics [4], [5], [6], [7], [8]. The limits to be considered by a DNSP may be different according to their operational requirements. Depending on the use case, the hosting capacity calculation can be broadly categorised as long-term, typically required

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for network planning [4], [6], [9], [10], [11], [12], [13], [14], and short-term or near real-time in recent years referred as operating envelopes (OEs), aimed at estimating and allocating network capacity available to all customers while preserving the operation within safe limits [15], [16], [17], [18], [19], [20]. This paper focuses on the use of OEs to support DER management and integration.

OEs define the technical limits within which network customers can import and export electricity while maintaining the local network within its physical constraints for operation [21]. A static operating envelope (SOE) refers to an OE with a static (time-invariant) limit, which is historically from 5 kW to 10 kW per phase for each residential customer and set based on operational conditions that may only occur on the network for 1% to 5% of the time in a year [21]. By definition, using an SOE leads to a conservative use of network capacity and may impose unnecessarily restrictive constraints on customers' power exports to and/or imports from the network. By contrast, a dynamic operating envelope (DOE) refers to an OE where capacity limits can change in time and are calculated and set dynamically according to real-time network conditions for better utilisation of network infrastructure. As the uptake of DERs in power distribution systems continues to grow, the transition from SOEs to DOEs has become a necessary response from distribution network service providers (DNSPs) and a change in customer connection models that has been described as one of the most significant in history [21].

OEs is widely recognised as a key enabler for the integration of DER into future network operational architectures [15], [22], [23], [24], [25], [26], [27]. In a similar way that constraints are used in transmission networks to manage security and reliability issues, OEs provide an efficient way to minimise operational issues in distribution networks as growing numbers of DERs are integrated into electricity markets [24].

In Australia, the currently favoured model for DER integration into electricity markets is the *hybrid framework* illustrated in Figure 1 [24]. This framework is currently undergoing practical demonstrations in the project Energy Demand and Generation Exchange (EDGE) [15] and project Symphony [16]. As shown in Fig. 1, the Australian Energy Market Operator (AEMO) receives the bids/offers from consumers or aggregators in both the transmission and distribution networks and operational data, including DOEs from distribution system operators (DSOs), and clears the market taking all constraints into account and generates dispatch signals. SOEs are predetermined during the process, while DOEs are calculated by DSO either day-ahead or in real-time and shared with both aggregators and AEMO to ensure dispatched DER generations will not incur any operational violations.

Key considerations in regards to the determination or calculation of OEs include:

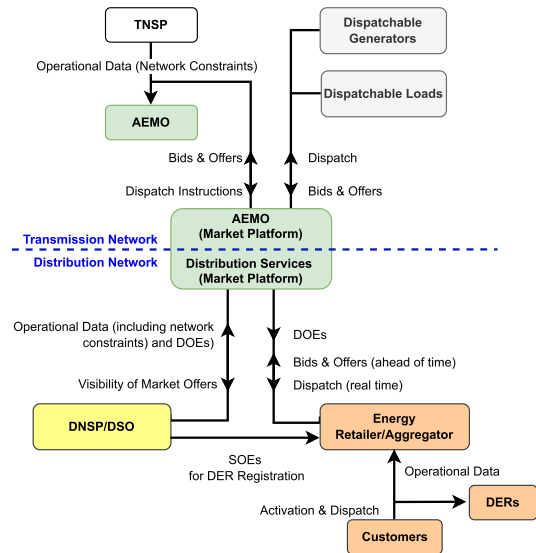


FIGURE 1. The Hybrid framework developed in the open energy networks project [24] (TNSP: Transmission Network Service Provider; DSO: Distribution system operator; Although AEMO is preferred to being the distribution system market operator in several project trials in Australia, this is still under discussion and has not been determined).

- SOEs should be calculated by DSO for DERs not involved in the market (passive customers) and updated regularly by DSOs.
- The operational characteristics of passive customers (without controllable DERs) can be regarded as fixed loads and their powers will be forecasted by DSOs. Other controllable network sources, e.g. on-load tap changer (OLTC) can also be optimised to achieve better DOEs.
- The approach to calculating DOEs in some projects relies on a fully visible network. However, as indicated in [21], diversity in calculating DOEs is expected for different DNSPs depending on the network visibility. In this paper, we also assume full visibility of the distribution network.
- Fairness should be carefully considered as discussed in [21], which can be achieved by setting appropriate objective functions and/or constraints in the formulation.
- Carefully setting or limiting reactive powers from controllable sources can also achieve better DOEs [15].

Various approaches have been proposed for OEs, such as adopting static capacity limits, e.g., 5 kW or 10 kW per phase for electricity exports, or time-varying limits determined based on unbalanced three-phase power flow (UTPF) calculations [17], [28], [29], unbalanced three-phase *optimal* power flow calculations [18], [20], as well as machine learning (ML)-based approaches [30].

However, a common unstated assumption in the implementation of OEs is that no operational violations are expected when the net generations of all customers in a local section of the network are within the OEs [15], [21]. This assumption

is critical to guarantee the validity of OEs as a reliable instrument to manage DERs. This assumption can be justified for a balanced radial network, where lower exports or higher imports from customers will result in lower currents running towards the reference bus in the network, which in turn leads to lower voltages along the network lines. In an unbalanced network, however, because different phases are mutually coupled, this assumption is not necessarily justified and needs to be examined more carefully, which motivates the present paper.

The main contributions of this paper are:

- 1) A theoretical analysis of nodal voltage sensitivities to power injections in an unbalanced distribution network is presented based on UTPF equations. These sensitivities in an LVDN are drastically more significant than in a transmission network due to mutual couplings and unbalances among all phases. The analysis shows that decreasing exporting power or increasing importing power of a single-phase connected customer may lead to *higher* voltage in an adjacent phase — potentially leading to operational violations — in contrast with what may be intuitively expected in a transmission network. Indicative nodal voltage sensitivities are mapped in a table of general simplified rules (Table 1).
- 2) The observations from the theoretical analysis are numerically tested on an illustrative two-bus system and on a real representative Australian network model from [31]. The simplified rules in Table 1 are validated by the simulation results, although it is noted that these simplified rules are only approximate and can become less accurate under extreme operational conditions.
- 3) The potential impacts of sensitivities in unbalanced distribution networks on the effectiveness of OEs are discussed, which underlines the importance of taking the model of measurement errors and uncertainties into account in order to obtain robust OEs.

The remainder of the paper is organised as follows. A typical approach to calculating DOEs, based on UTPF, is presented in Section II, followed by the sensitivity analysis and its impact on the robustness of OEs via a two-bus system in Section III. The observations of the analysis are tested on a numerical case study for the two-bus system, and for a real representative Australian LVDN in Section IV-A. The paper concludes with a few final remarks in Section V.

II. UTPF-BASED DOE CALCULATION

From the aforementioned approaches reported in the literature to calculate DOEs, including based on power flow (PF) [17], [28], [29], optimal power flow (OPF) [18], [20] and ML techniques [30], the present paper adopts a simple UTPF approach following [17], [29] and based on the PF formulation:

$$V_{i_{ref}}^\phi = V_0^\phi \quad \forall \phi, \forall i, \quad (1a)$$

$$V_i^\phi - V_j^\phi = \sum_{\psi} z_{ij}^{\phi\psi} I_{ij}^\phi \quad \forall \phi, \quad \forall ij \in \mathcal{L}, \quad (1b)$$

$$V_i^\phi = k_{ij} V_j^\phi \quad \forall \phi, \quad \forall ij \in \mathcal{T}, \quad (1c)$$

$$\sum_{n:n \rightarrow i} k_{ni} I_{ni}^\phi - \sum_{m:i \rightarrow m} I_{im}^\phi = - \sum_m I_{i,m}^\phi \quad \forall \phi, \quad \forall i, \quad (1d)$$

$$I_{i,m}^\phi = \frac{\mu_{\phi,i,m} (P_m^{pre} - jQ_m^{pre})}{(V_i^\phi)^*} \quad \forall \phi, \quad \forall i, \quad \forall m \in \mathcal{PC}, \quad (1e)$$

$$I_{i,m}^\phi = \frac{\mu_{\phi,i,m} (P_m^{DOE} - jQ_m^{pre})}{(V_i^\phi)^*} \quad \forall \phi, \quad \forall i, \quad \forall m \in \mathcal{DOE}, \quad (1f)$$

$$I_{i,m}^\phi = \frac{\mu_{\phi,i,m} (P_m^{SOE} - jQ_m^{pre})}{(V_i^\phi)^*} \quad \forall \phi, \quad \forall i, \quad \forall m \in \mathcal{SOE}, \quad (1g)$$

where i_{ref} is the index of the reference bus and V_0^ϕ is the fixed voltage at phase ϕ (known parameter); V_i^ϕ is the voltage of phase ϕ at node i ; $z_{ij}^{\phi\psi}$ is the mutual impedance between phase ϕ and phase ψ in line ij ; \mathcal{L} and \mathcal{T} are the set of distribution lines and transformers, respectively; I_{ni}^ϕ is the current in line ni : flowing from bus n to bus i ; k_{ij} is the tap ratio the transformer between bus i and bus j , and $k_{ij} = 1$ for distribution lines; $I_{i,m}^\phi$ is the current contribution to phase ϕ of bus i from customer m ; P_m^{pre} is the predicted active power injection of passive customer m while Q_m^{pre} is its forecasted reactive power; P_m^{DOE} is the export limit of customer m with DOEs, while P_m^{SOE} is the export limit of customer m with SOEs; $\mu_{\phi,i,m} \in \{0, 1\}$ is a parameter indicating the phase connection of customer m with its value being 1 if it is connected to phase ϕ of bus i and being 0 otherwise; \mathcal{PC} , \mathcal{DOE} , \mathcal{SOE} denote the sets of passive customers, active customers with DOEs, and active customers with SOEs.

In this formulation, (1a) defines the voltage at the reference bus, and (1b)-(1c) represent voltage drop equations along lines and ideal transformers. The Kirchhoff current law is expressed by (1d), and (1e)-(1g) represent the current contributions of each customer type, as passive customers, or customers with DOEs or SOEs, to their connected buses.

Note that although reactive powers of controllable customers can also be treated as variables in calculating DOEs, they are fixed at forecasted values in this paper. Forecasting and quantifying the impact of reactive power on DOEs are interesting and technically challenging problems beyond the scope of the present paper.

Under the assumptions that: (i) the upper limit of nodal voltage is V_i^{max} for a bus i and voltage compliance is the only factor to be considered in calculating DOEs, and (ii) all customers are subject to the same DOE, say P^{DOE} , then P^{DOE} can be calculated using a bisection algorithm initialised from reasonable DOE bounds, as shown in Algorithm 1. The bisection algorithm is a simple numerical approach commonly used in power system operation assessments (e.g., [32], [33]), and it can naturally be applied in PF-based approaches to calculating DOEs with guaranteed convergence. The UTPF can be formulated and

Algorithm 1 Bisection Algorithm to Calculate DOEs

- 1: **Initialisation:** Set the upper bound of P^{DOE} as $P_{ub}^{DOE} = 15 \text{ kW}$ and the lower bound as $P_{lb}^{DOE} = 0 \text{ kW}$. Set the convergence tolerance value as $\epsilon_{doe} = 10^{-5}$, and upper limit of voltage magnitude as V^{\max} .
- 2: **while** $(P_{ub}^{DOE} - P_{lb}^{DOE})/2 > \epsilon_{doe}$ **do**
- 3: Update the DOEs for all relevant customers as $(P_{ub}^{DOE} + P_{lb}^{DOE})/2$.
- 4: Run UTPF and record the maximum voltage magnitude value in the network as \tilde{V}^{\max} .
- 5: If $\tilde{V}^{\max} > V^{\max}$, update $P_{ub}^{DOE} = (P_{ub}^{DOE} + P_{lb}^{DOE})/2$. Otherwise, update $P_{lb}^{DOE} = (P_{ub}^{DOE} + P_{lb}^{DOE})/2$.
- 6: **end while**
- 7: Report the final DOE value as $(P_{ub}^{DOE} + P_{lb}^{DOE})/2$.

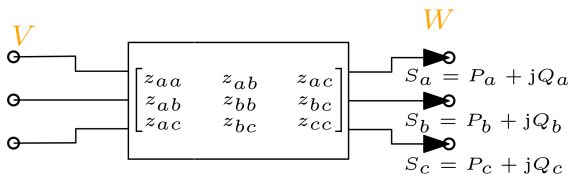


FIGURE 2. A two-bus system for discussing the effectiveness of DOEs.

solved with off-the-shelf solvers, e.g. OpenDSS [34] and PowerModelsDistribution.jl [35]. It is noteworthy that the UTPF-based approach can also be formulated as an equivalent optimisation problem, similar to the one discussed in [18].

III. SENSITIVITY ANALYSIS AND ITS IMPACT ON THE EFFECTIVENESS OF OEs

The effectiveness of OEs, through theoretical analysis, will be further investigated in this section based on the sensitivities of nodal voltages to customers' power injections. Taking the two-bus illustrative system, as shown in Fig.2, as an example, the voltage at bus 1 is fixed and denoted as V , and the voltage at bus 2 is denoted as W . The impedance matrix of the line connecting bus 1 and bus 2 is z , and three customers are connected to phase a to phase c of bus 2.

For the illustrative example, the following power flow equations can be derived straightforwardly.

$$V_\phi - W_\phi = \sum_{\psi \in \{a,b,c\}} z_{\phi\psi} I_\psi \quad \forall \phi \quad (2a)$$

$$S_\phi = W_\phi I_\phi^* \quad \forall \phi \quad (2b)$$

Equivalently, (2) can be reformulated as

$$V_\phi - W_\phi = \sum_{\psi \in \{a,b,c\}} z_{\phi\psi} \frac{P_\psi - jQ_\psi}{W_\psi^*} \quad \forall \phi \quad (3)$$

Taking phase a as an example, (3) can also be expanded as

$$V_a - W_a = \frac{(r_{aa}P_a + x_{aa}Q_a) + j(x_{aa}P_a - r_{aa}Q_a)}{W_a^*}$$

$$+ \frac{(r_{ab}P_b + x_{ab}Q_b) + j(x_{ab}P_b - r_{ab}Q_b)}{W_b^*} + \frac{(r_{ac}P_c + x_{ac}Q_c) + j(x_{ac}P_c - r_{ac}Q_c)}{W_c^*} \quad (4)$$

where $r_{\phi\psi}$ and $x_{\phi\psi}$ are the resistance and reactance of line $\phi\psi$, i.e., $z_{\phi\psi} = r_{\phi\psi} + jx_{\phi\psi}$.

A commonly used approximation in distribution network analysis is to replace W_a , W_b and W_c on the right side of (4) by their nominal values or estimated values [36], [37], [38]. For the convenience of following derivations, in this paper, they will be replaced by their nominal values, which are $U_a = U_0$, $U_b = U_0(-\frac{1}{2} - j\frac{\sqrt{3}}{2})$ and $U_c = U_0(-\frac{1}{2} + j\frac{\sqrt{3}}{2})$ for phase a , b and c , respectively, with U_0 being a known parameter. Also, as voltage angles in phase a , b and c are usually close to 0° , -120° and 120° respectively, we further take the approximation: $|W_a| \approx \Re(W_a)$, $|W_b| \approx \Re(W_b e^{j\frac{2\pi}{3}})$ and $|W_c| \approx \Re(W_c e^{j\frac{-2\pi}{3}})$, where $\Re(\cdot)$ denotes the real and imaginary parts of a complex number.

Replacing W_a , W_b and W_c on its right hand side by U_a , U_b and U_c , (4) can be approximated as

$$\begin{aligned} |V_a| - |W_a| &\approx \Re(V_a) - \Re(W_a) \\ &\approx \sum_{\psi \in \{a,b,c\}} \Re \left[\frac{(r_{a\psi}P_\psi + x_{a\psi}Q_\psi) + j(x_{a\psi}P_\psi - r_{a\psi}Q_\psi)}{U_\psi^*} \right] \end{aligned} \quad (5a)$$

$$\begin{aligned} &= \frac{r_{aa}P_a + x_{aa}Q_a}{U_0} - \frac{(r_{ab} - \sqrt{3}x_{ab})P_b + (\sqrt{3}r_{ab} + x_{ab})Q_b}{2U_0} \\ &\quad - \frac{(r_{ac} + \sqrt{3}x_{ac})P_c + (-\sqrt{3}r_{ac} + x_{ac})Q_c}{2U_0} \end{aligned} \quad (5b)$$

Details of the derivation from (5a) to (5b) can be found in the Appendix.

As P_a , Q_a , P_b , Q_b , P_c and Q_c are independent of each other, sensitivities of $|W_a|$ to P_ϕ ($\forall \phi$) and Q_ϕ ($\forall \phi$) can be easily derived as follows.

$$\begin{aligned} \frac{\partial |W_a|}{\partial P_a} &\approx \frac{-r_{aa}}{U_0}, & \frac{\partial |W_a|}{\partial Q_a} &\approx \frac{-x_{aa}}{U_0} \\ \frac{\partial |W_a|}{\partial P_b} &\approx \frac{r_{ab} - \sqrt{3}x_{ab}}{U_0}, & \frac{\partial |W_a|}{\partial Q_b} &\approx \frac{\sqrt{3}r_{ab} + x_{ab}}{U_0} \\ \frac{\partial |W_a|}{\partial P_c} &\approx \frac{r_{ac} + \sqrt{3}x_{ac}}{U_0}, & \frac{\partial |W_a|}{\partial Q_c} &\approx \frac{-\sqrt{3}r_{ac} + x_{ac}}{U_0} \end{aligned} \quad (6)$$

Then for any changes in power demands, voltage variations can be expressed as

$$\begin{aligned} \Delta |W_a| &= \frac{\partial |W_a|}{\partial P_a} \Delta P_a + \frac{\partial |W_a|}{\partial Q_a} \Delta Q_a + \frac{\partial |W_a|}{\partial P_b} \Delta P_b \\ &\quad + \frac{\partial |W_a|}{\partial Q_b} \Delta Q_b + \frac{\partial |W_a|}{\partial P_c} \Delta P_c + \frac{\partial |W_a|}{\partial Q_c} \Delta Q_c \quad (7a) \\ &\approx \frac{-r_{aa}}{U_0} \Delta P_a + \frac{-x_{aa}}{U_0} \Delta Q_a \end{aligned}$$

TABLE 1. Sensitivity of $|W|$ to customer's demand (+: non-negative; -: non-positive; ~: uncertain. Symbols in the bracket will replace "~" when $r_{\phi\psi} - \sqrt{3}x_{\phi\psi} \leq 0$ ($\phi \neq \psi$) and $-\sqrt{3}r_{\phi\psi} + x_{\phi\psi} \geq 0$ ($\phi \neq \psi$)).

Demand/Voltage	$ W_a $	$ W_b $	$ W_c $
P_a	-	+	~ (-)
Q_a	-	~ (+)	+
P_b	~ (-)	-	+
Q_b	+	-	~ (+)
P_c	+	~ (-)	-
Q_c	~ (+)	+	-

$$\begin{aligned}
 & + \frac{r_{ab} - \sqrt{3}x_{ab}}{2U_0} \Delta P_b + \frac{\sqrt{3}r_{ab} + x_{ab}}{2U_0} \Delta Q_b \\
 & + \frac{r_{ac} + \sqrt{3}x_{ac}}{2U_0} \Delta P_c + \frac{-\sqrt{3}r_{ac} + x_{ac}}{2U_0} \Delta Q_c \quad (7b)
 \end{aligned}$$

Several remarks are given below based on the above sensitivity analysis.

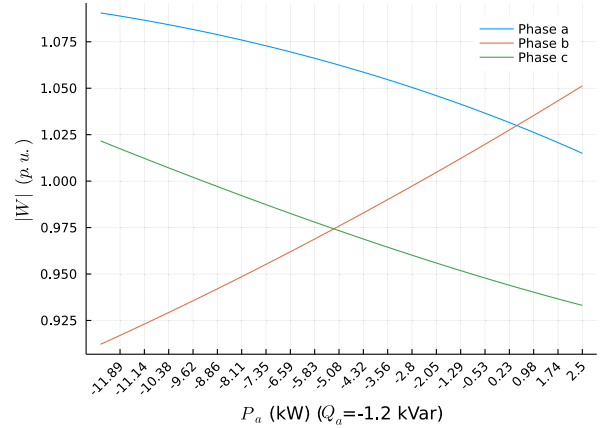
- 1) As there are usually $r_{\phi\psi} \geq 0$ and $x_{\phi\psi} \geq 0$, (7b) implies that increasing P_a and Q_a will lead to smaller $|W_a|$. On the contrary, $|W_a|$ will increase when Q_b or P_c becomes larger.
- 2) The sensitivity of $|W_a|$ to P_b and Q_c depends on the values of $r_{ab} - \sqrt{3}x_{ab}$ and $-\sqrt{3}r_{ac} + x_{ac}$, respectively. Unlike in transmission network, $r_{\phi\psi}$ and $x_{\phi\psi}$ in distribution network may be close to each other, making the symbols of both $r_{ab} - \sqrt{3}x_{ab}$ and $-\sqrt{3}r_{ac} + x_{ac}$ uncertain.
- 3) Based on the analysis, the sensitivities of voltage at bus 2 to each customer's varying demands can be deduced and summarised in Table 1. The results imply that increasing a customer's active demand (either to a lower export or a higher import) could help alleviate the over-voltage issue in its connected phase, which, however, may lead to an over-voltage issue in its next-adjacent phase (phase b for phase a , phase c for phase b and phase a for phase c). Similarly, increasing a customer's reactive demand could help alleviate the over-voltage issues in its connected phase, which on the other hand can lead to over-voltage issues in its pre-adjacent phase (phase b for phase c , phase c for phase a and phase b for phase c).
- 4) Generally, if there is still $x_{\phi\psi} \geq r_{\phi\psi}$, which means $r_{ab} - \sqrt{3}x_{ab} \leq 0$ and $-\sqrt{3}r_{ac} + x_{ac} \geq 0$,¹ increasing P_b and Q_c for the illustrative example could lead to lower and higher values of $|W_a|$, respectively.

In summary, the sensitivity analysis implies that OEs, either as SOEs or from a deterministic approach based on UTPF or UTOPTF when generation/demand variations are not considered, cannot guarantee operational security (voltage within the upper limit in this case) even if each customer's export is under its allocated capacity limits.

¹The parameters for the two-bus illustrative example provided in Section IV-A meet this condition.

TABLE 2. Parameters for the two-bus illustrative example.

Parameter	Value		
V (p.u.)	1.00		
W	Variable		
z (Ω)	0.3465 + j1.0179 0.1560 + j0.5017 0.1580 + j0.4236	0.1560 + j0.5017 0.3375 + j1.0478 0.1535 + j0.3849	0.1580 + j0.4236 0.1535 + j0.3849 0.3414 + j1.0348
$S_a^0 = P_a^0 + jQ_a^0$ (kVA)	5.00+j1.00		
$S_b^0 = P_b^0 + jQ_b^0$ (kVA)	5.00+j1.00		
$S_c^0 = P_c^0 + jQ_c^0$ (kVA)	5.00+j1.00		


FIGURE 3. Values of $|W_a|$, $|W_b|$ and $|W_c|$ along with varying P_a .

It is also noteworthy that the results in Table 1 are based on the two-bus system, where a strong coupling exists for any two phases. However, if the two phases are weakly coupled, the true sensitivities may differ due to the errors brought by the approximations taken for deriving the results in Table 1. Further, even for the two-bus system, some of the derived rules in Table 1 may become invalid under extreme conditions in an unbalanced network and more discussions can be found in the appendix.

Another interesting point is that the voltage violations in one phase caused by the power variations in other phases are not common or have not been raised as an issue in transmission networks, which, based on (7b), can also be explained. Generally, the powers of three phases are balanced in a transmission network, which, again taking phase a as an example based on the two-bus system, implies

$$\begin{aligned}
 \Delta |W_a| \approx & \frac{-2r_{aa} + r_{ab} - \sqrt{3}x_{ab} + r_{ac} + \sqrt{3}x_{ac}}{2U_0} \Delta \tilde{P} \\
 & + \frac{-2x_{aa} + \sqrt{3}r_{ab} + x_{ab} - \sqrt{3}r_{ac} + x_{ac}}{2U_0} \Delta \tilde{Q} \quad (8)
 \end{aligned}$$

where $\Delta \tilde{P}$ and $\Delta \tilde{Q}$ are the average active and reactive power variations of three phases.

Noting that in a transmission network, we usually have $x_{\phi\psi} \gg r_{\phi\psi} \approx 0$, $x_{\phi\phi} \geq x_{\phi\psi}$ and $x_{\phi\psi} \approx x_{\phi\phi}$, which implies

$$-2r_{aa} + r_{ab} - \sqrt{3}x_{ab} + r_{ac} + \sqrt{3}x_{ac} \approx 0 \quad (9a)$$

$$-2x_{aa} + \sqrt{3}r_{ab} + x_{ab} - \sqrt{3}r_{ac} + x_{ac} \leq 0 \quad (9b)$$

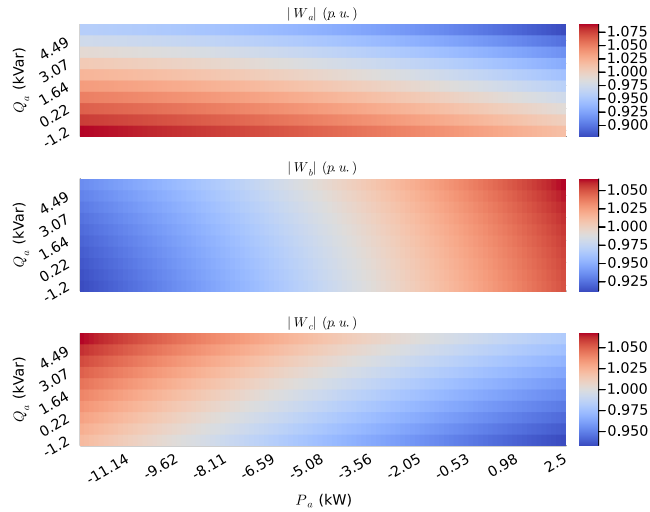


FIGURE 4. Values of $|W|$ along with varying P_a and Q_a .

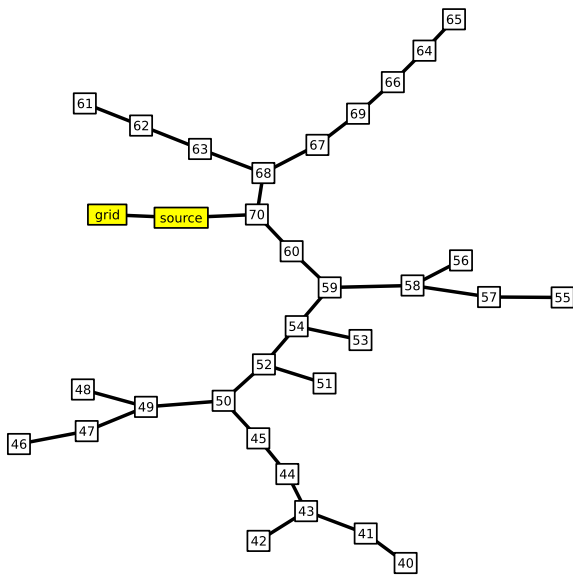


FIGURE 5. Network topology of the real network (Upstream grid (reference bus) and its connected bus are marked in yellow).

and a positive $\Delta\tilde{P}$ will have neglectable impacts on the network voltages, while a positive $\Delta\tilde{Q}$ generally tends to cause lower voltage level in phase a . Therefore, the impact of powers on voltages in transmission networks aligns with our intuitive expectations.

IV. CASE STUDY

A. THE TWO-BUS SYSTEM

In this section, the sensitivity analysis will be further studied based on the two-bus illustrative system with parameters given in Table 2 and the nominal phase-to-phase voltage of the network is 400 V.

By fixing $S_b = S_b^0, S_c = S_c^0$ and changing P_a and Q_a with a small stepwise in the range of $[-0.5P_a^0, 2.5P_a^0]$ and $[-0.6Q_a^0, 2.6Q_a^0]$, respectively, the voltage magnitude

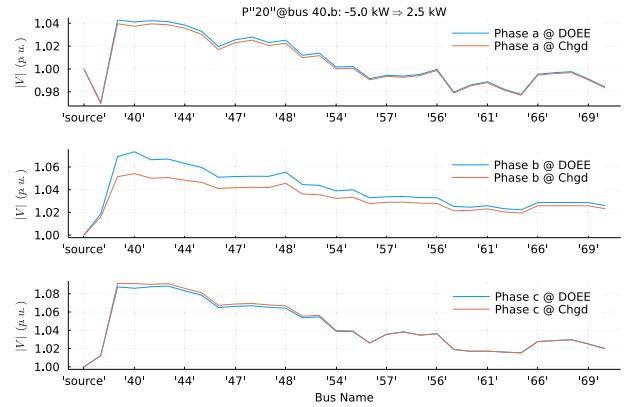


FIGURE 6. Values of $|W_a|, |W_b|$ and $|W_c|$ in the network along customer load variation (lower export).

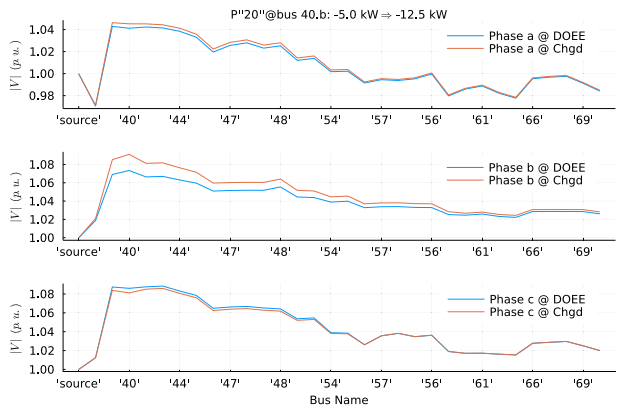


FIGURE 7. Values of $|W_a|, |W_b|$ and $|W_c|$ in the network along customer load variation (higher export).

at bus 2, i.e. $|W|$, for phase a to c are presented in Fig.3 and Fig.4.

Based on the parameters given in Table 2, we indeed have $r_{\phi\psi} - \sqrt{3}x_{\phi\psi} \leq 0 (\phi \neq \psi)$ and $-\sqrt{3}r_{\phi\psi} + x_{\phi\psi} \geq 0 (\phi \neq \psi)$, which means increasing P_a will lead to lower, higher and lower voltage levels in phase a, b and c , respectively. Similarly, lower, higher and higher voltage levels in phases a, b and c are expected with increasing Q_a , respectively. In conclusion, theoretical analysis in Section III are demonstrated by simulation results presented in Fig.3 and Fig.4.

B. A REAL AUSTRALIAN NETWORK

In this subsection, a real representative Australian LVDN will be studied to investigate both the sensitivities and their impact on the effectiveness of DOEs. The topology of the network is given in Fig.5.

Network parameters can be found in [31], where the transformer has been changed to Y_n/Y_n connection with $R\% = 5$ and $X\% = 7$. The voltage at the reference bus, grid in Fig.5, is set as $[1.0, 1.0e^{-j\frac{2\pi}{3}}, 1.0e^{j\frac{2\pi}{3}}]^T$ and all the customers are set as the same active demand -5 kW (exporting power at 5 kW). The reactive demands of all customers are set as 2 kVar.

In this study, the exporting power of a randomly selected customer will be increased and decreased by 7.5 kW, respectively, based on which the voltage variations in the network will be investigated. The simulation results are presented in Fig.6 and Fig.7.

As indicated by the results, the active demand of customer “20” connected to phase *b* of bus “40” has increased from -5 kW to 2.5 kW in Fig.6, leading to lower voltage levels of both phase *a* and phase *b*, and higher voltage level in phase *c* in the network, which is consistent with the theoretical analysis in Section III.

Similarly, if the active demand of customer “20” further decreases to -12.5 kW as shown in Fig.7, higher voltage levels in both phase *a* and phase *b*, and lower voltage levels in phase *c* in the network are observed, which again validate the theoretical analysis in Section III.

Further, we will analyse the network’s voltage behaviour together with operating envelopes by taking the following assumptions for the Australian LVDN.

- 1) The upper voltage limit is set as 1.05 p.u., i.e. $V_i^{\max} = 1.05 \text{ p.u. } (\forall i)$. Customers “1”, “11”, \dots , “81”, which are connected to phase *b*, *b*, *c*, *a*, *c*, *c*, *b*, *a* and *b* respectively, are with DOEs while all the other customers are with SOEs with the value for each of them as 1 kW.
- 2) Reactive power for each of all the customers is fixed at 0.5 kVar.
- 3) Initially, all customers are generating powers at their exporting limit specified by DOEs or SOEs.

DOEs are calculated based on the approach presented in Section II, and the reported DOE value for each of all the customers is 2.91 kW. Next, several OE scenarios will be analysed by changing the DOEs of *n* customers to 0 kW, where *n* will take the value in the range [1, 2, \dots , 9].

Although the true generated power may be different from 0 kW in a real network, such a situation that some customers exporting powers at their capacity limits while other customers are exporting powers at 0 kW or even importing power is possible due to:

- 1) The sudden change in solar irradiance leading to significant PV output variations.
- 2) The load variations.
- 3) The operation of existing home battery systems, which is being charged during some periods.
- 4) Customers responding to the market via demand response or to provide other ancillary services.
- 5) The failure or maintenance of PV systems.
- 6) A combination of one or several above factors.

Simulation results are presented in Fig.8, which demonstrates that for the studied system if six or fewer of the nine customers with DOEs reduce the exporting power to 0 kW, there is a chance that voltage violation will occur. However, when there are seven or more customers with varied power outputs, voltage violation can be avoided, which is because the impacts of varied power outputs on the network’s voltage

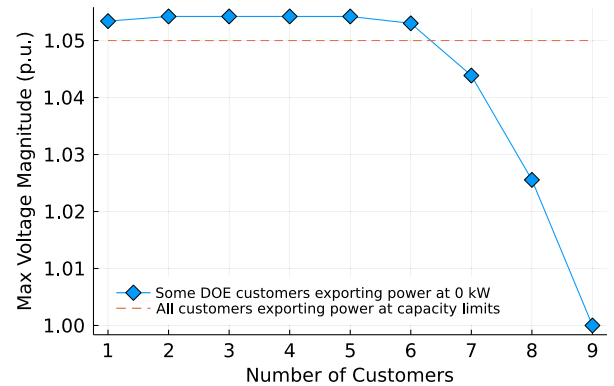


FIGURE 8. Maximum voltage magnitude in the network after the power outputs of *n* customers with DOEs vary: exporting 2.91 kW \Rightarrow exporting 0kW.

brought by these customers can be cancelled out due to the diversity of their connected phases.

In fact, the value of DOEs is determined after the voltage at phase *c* of bus “40” reaches the upper limit, which means any decrease in exporting power in phase *b* tends to cause higher voltage in phase *c* according to Table 1. When $n = 1$, we found that voltage violations were detected at phase *c* of bus “40” when the exporting powers of customer 61 (connected to bus “53”) and customer 81 (connected to bus “41”) decreased, leading to the highest voltage magnitude to 1.0519 p.u. and 1.0534 p.u., respectively.

However, although customer 1 (connected to bus “69”) and customer 11 (connected to bus “67”) are connected to phase *b*, variations of their exporting powers lead to minimal voltage variations to phase *c* of bus “40”, both of which are 1.04997 p.u. This, on the other hand, demonstrates that if the two buses are weakly coupled,² their mutual impacts will be neglectable.

V. CONCLUSION

As an essential piece in future DER integration architecture, operating envelopes can help address some operational challenges, especially voltage issues, in distribution networks. However, due to the coupling phases and unbalances in the distribution networks, voltage behaviour responding to demand variations becomes more complex. Both the theoretical analysis and case study reveals that decreasing export or increasing import in one phase can indeed help address the over-voltage issue in this phase, which, however, can lead to or worsen the over-voltage issues in its adjacent phases.

Therefore, the SOEs or OEs calculated by a deterministic approach without considering generation/demand variations may not be able to guarantee security of the distribution network, which requires the consideration of uncertainties, either from varying PV generation or electricity consumption,

²The common lines of the route from bus “67” or “69” to the reference bus (bus “grid”) and the route from bus “40” to the reference bus are “grid-source” (the internal impedance of the voltage source) and “source-70” (the transformer with zero mutual impedance), where the mutual impedance of any two phases is $0 + j0 \Omega$.

to produce robust OEs. Investigating efficient methods to get robust OEs falls within our future research interests.

APPENDIX

A. FURTHER DERIVATIONS OF SENSITIVITIES OF NODAL VOLTAGE TO POWER INJECTIONS

For phase *a*, noting that $\Re(U_a) \approx U_a$, it is obvious that

$$\Re \left[\frac{(r_{aa}P_a + x_{aa}Q_a) + j(x_{aa}P_a - r_{aa}Q_a)}{U_a^*} \right] \approx \frac{(r_{aa}P_a + x_{aa}Q_a)}{U_0} \tag{10}$$

For phase *b* with $\Re(U_b) \approx U_b e^{j\frac{2\pi}{3}}$, we have

$$\Re \left[\frac{(r_{ab}P_b + x_{ab}Q_b) + j(x_{ab}P_b - r_{ab}Q_b)}{U_b^*} \right] \tag{11a}$$

$$= \Re \left[\frac{[(r_{ab}P_b + x_{ab}Q_b) + j(x_{ab}P_b - r_{ab}Q_b)]U_b}{|U_b|^2} \right] \tag{11b}$$

$$\approx \Re \left[-\frac{[(r_{ab}P_b + x_{ab}Q_b) + j(x_{ab}P_b - r_{ab}Q_b)](1 + j\sqrt{3})}{2U_0} \right] \tag{11c}$$

$$= -\frac{r_{ab}P_b + x_{ab}Q_b - \sqrt{3}x_{ab}P_b + \sqrt{3}r_{ab}Q_b}{2U_0} \tag{11d}$$

$$= -\frac{r_{ab} - \sqrt{3}x_{ab}}{2U_0}P_b - \frac{\sqrt{3}r_{ab} + x_{ab}}{2U_0}Q_b \tag{11e}$$

Similarly for phase *c*, we have $\Re(U_c) \approx U_c e^{-j\frac{2\pi}{3}}$ and

$$\Re \left[\frac{(r_{ac}P_c + x_{ac}Q_c) + j(x_{ac}P_c - r_{ac}Q_c)}{U_c^*} \right] = -\frac{r_{ac} + \sqrt{3}x_{ac}}{2U_0}P_c - \frac{-\sqrt{3}r_{ac} + x_{ac}}{2U_0}Q_c \tag{12}$$

It is also noteworthy that similar expressions on the sensitivities were also derived from different approaches and discussed in [39], [40], and [41].

B. DISCUSSIONS ON THE VALIDITY OF DERIVED RESULTS ON SENSITIVITY ANALYSIS

As discussed previously, even for the two-bus system, some of the derived results for sensitivity analysis in Table 1 may become invalid under extreme conditions in an unbalanced network.

Taking again phase *a* in the two-bus illustrative network as an example and with (2a), we have

$$|V_a|^2 = |W_a|^2 + W_a \Delta W_a^* + W_a^* \Delta W_a + |\Delta W_a|^2 \tag{13}$$

where $\Delta W_a = \sum_{\phi} (r_{a\phi} + jx_{a\phi})I_{\phi}$.

Then the expression can be further expanded as

$$(|V_a| + |W_a|)(|V_a| - |W_a|) = 2\Re(W_a \Delta W_a^* + W_a^* \Delta W_a) + |\Delta W_a|^2 \tag{14}$$

Noting that $\Delta W_a = V_a - W_a$, which implies that the second order of its value, $|\Delta W_a|^2$, can be sufficiently small, this item is approximated as 0 [39]. After replacing I_{ϕ} in (13) by (2b),

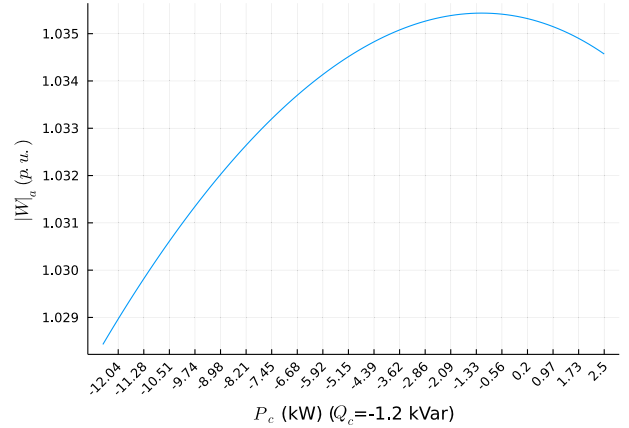


FIGURE 9. Values of $|W_a|$ along with varying P_c under extreme network conditions.

(15) can be derived (15a)–(15e), as shown at the top of the next page.

Further assuming that $\theta_{\phi} \in [\theta_{\phi}^0 - \Delta\theta, \theta_{\phi}^0 + \Delta\theta]$ with θ_a^0, θ_b^0 and θ_c^0 being $0^\circ, -120^\circ$ and 120° , respectively. Then we have $\theta_{\phi\psi}^0 - 2\Delta\theta \leq \theta_{\phi\psi} \leq \theta_{\phi\psi}^0 + 2\Delta\theta$, where $\theta_{\phi\psi}^0 = \theta_{\phi}^0 - \theta_{\psi}^0$. Taking the derivatives of both the left and right sides of (15e) to P_a and Q_a leads to

$$\frac{\partial |W_a|}{\partial P_a} = -\frac{r_{aa}}{2|W_a|} \leq 0, \quad \frac{\partial |W_a|}{\partial Q_a} = -\frac{x_{aa}}{2|W_a|} \leq 0 \tag{16a}$$

which implies increasing demands in phase *a* will always lead to a lower voltage level of this phase for bus 2.

Similarly for $\frac{\partial |W_a|}{\partial P_{\phi}}$ and $\frac{\partial |W_a|}{\partial Q_{\phi}}$ with $\phi \in \{b, c\}$, we have³

$$\frac{\partial |W_a|}{\partial P_{\phi}} \approx -\frac{r_{a\phi} \cos \theta_{a\phi} + x_{a\phi} \sin \theta_{a\phi}}{2|W_{\phi}|} \tag{17a}$$

$$\frac{\partial |W_a|}{\partial Q_{\phi}} \approx -\frac{-r_{a\phi} \sin \theta_{a\phi} + x_{a\phi} \cos \theta_{a\phi}}{2|W_{\phi}|} \tag{17b}$$

Taking $\phi = b$ as an example, as θ_{ac} is around -120° , the sign of $\frac{\partial |W_a|}{\partial Q_c}$ is always uncertain. However, for $\frac{\partial |W_a|}{\partial P_c}$ that is generally positive as discussed in Section III, to ensure it is positive, we need

$$r_{ac} \cos \theta_{ac} + x_{ac} \sin \theta_{ac} \leq 0 \tag{18}$$

As generally there is $\Delta\theta \in (-30^\circ, 30^\circ)$, we have $-180^\circ < \theta_{ac} < -60^\circ$ and $\sin \theta_{ac} < 0$. Then (18) is equivalent to

$$\frac{x_{ac}}{r_{ac}} \geq -\cot \theta_{ac} = -\frac{\cos \theta_{ac}}{\sin \theta_{ac}} \tag{19}$$

As $-\cot \theta_{ac} \leq 0$ when $-180^\circ < \theta_{ac} \leq -90^\circ$, which implies (19) is always valid, and $-\cot \theta_{ac} > 0$ when $-90^\circ < \theta_{ac} < -60^\circ$, (19) may become invalid under extreme conditions in an unbalanced network.

³The exact expressions of $\frac{\partial |W_a|}{\partial P_{\phi}}$ and $\frac{\partial |W_a|}{\partial Q_{\phi}}$ are very complicated noting that $|W_a|, |W_b|, |W_c|, \sin \theta_{a\phi}$ and $\cos \theta_{a\phi}$ are all dependant on P_{ϕ} or Q_{ϕ} . For simplicity, we assume that $\frac{|W_a|}{|W_{\phi}|}(r_{a\phi} \cos \theta_{a\phi} + x_{a\phi} \sin \theta_{a\phi})$ and $\frac{|W_a|}{|W_{\phi}|}(x_{a\phi} \cos \theta_{a\phi} - r_{a\phi} \sin \theta_{a\phi})$ are invariants throughout the derivations of both $\frac{\partial |W_a|}{\partial P_{\phi}}$ and $\frac{\partial |W_a|}{\partial Q_{\phi}}$.

$$(|V_a| + |W_a|)(|V_a| - |W_a|) \approx 2\Re \left[\frac{W_a^*(r_{a\phi} + jx_{a\phi})(P_a - jQ_a)}{W_\phi^*} \right] \quad (15a)$$

$$= 2\Re \left[\sum_{\phi \in \{a,b,c\}} \frac{W_a^*(r_{a\phi} + jx_{a\phi})(P_\phi - jQ_\phi)}{W_\phi^*} \right] \quad (15b)$$

$$= 2\Re \left[(r_{aa} + jx_{aa})(P_a - jQ_a) + \sum_{\phi \in \{b,c\}} \left(\frac{|W_a|(r_{a\phi} + jx_{a\phi})(P_\phi - jQ_\phi)(\cos \theta_{a\phi} - j \sin \theta_{a\phi})}{|W_\phi|} \right) \right] \quad (15c)$$

$$= r_{aa}P_a + x_{aa}Q_a + \sum_{\phi \in \{b,c\}} \left(\frac{|W_a|}{|W_\phi|} [(r_{a\phi}P_\phi + x_{a\phi}Q_\phi) \cos \theta_{a\phi} + (x_{a\phi}P_\phi - r_{a\phi}Q_\phi) \sin \theta_{a\phi}] \right) \quad (15d)$$

$$= r_{aa}P_a + x_{aa}Q_a + \sum_{\phi \in \{b,c\}} \times \left(\frac{|W_a|}{|W_\phi|} (r_{a\phi} \cos \theta_{a\phi} + x_{a\phi} \sin \theta_{a\phi})P_\phi + \frac{|W_a|}{|W_\phi|} (x_{a\phi} \cos \theta_{a\phi} - r_{a\phi} \sin \theta_{a\phi})Q_\phi \right) \quad (15e)$$

where $\theta_{a\phi} = \theta_a - \theta_\phi$ with θ_ϕ being the angle of W_ϕ .

For example, assuming that $V_a = 1.0e^{j\frac{\pi}{9}}$ p.u., $V_b = 1.0e^{-j\frac{2\pi}{3}}$ p.u. and $V_c = 1.0e^{j\frac{5\pi}{9}}$ p.u., simulation results by increasing P_c when $r_{ac} > 0$, $x_{ac} = 0$ and $x_{ac}/r_{ac} = 0$ are presented in Fig.9, where increasing P_c leads to higher voltage level when $P_c \leq -1.17$ kW, and then to lower voltage level when $P_c > -1.17$ kW.⁴ The simulation results further demonstrate the complexity of the voltage behaviour in an unbalanced distribution network and the importance of keeping a more balanced network to confidently operate a distribution network when applying OEs.

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⁴As $\frac{\partial |W_a|}{\partial P_c}$ is derived with approximations, its value is still positive under such extreme operational condition when $P_c \leq -1.17$ kW, which is not perfectly aligned with the theoretical derivation above.

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